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Fire Protection Provision of Structures from FHA Perspective

Prateep Roy

Formerly with, TATA Consulting Engineers Limited, Mumbai, India.
E-mail ID: roypk@yahoo.com

Abstract

It is observed that in many civil structures, passive fire protection requirement is arrived at by prescriptive methods recommended by National Building Code (NBC) or Indian Standards rather than analyzing from fire safety point of view using standard technique like Fire Hazard Analysis (FHA). FHA helps in analyzing the fire hazard aspects in terms of possible fire scenarios, consequences of fire deterministically/probabilistically; judges the adequacy of fire protection for prevention, detection, suppression, extinction and containment of fire and its effects. It is observed that almost in all cases of fire protection of civil structures, the resources are not properly used nor safety is assessed in the way it should be. Improper resource utilization results in environmental concern besides the economic aspect of a project. This paper discusses the passive fire protection measures for civil structures from FHA point of view with outcome derived from fire dynamics simulation and suggests the changes required to be made in regulatory requirement in the context of passive fire protection for civil structures, in particular. It also emphasizes the need of FHA for arriving at the fire barrier ratings of fire barriers /walls.

Peer-review under responsibility of the Indira Gandhi Centre for Atomic Research

Keywords: FHA, Passive Fire Protection, Civil Structures, Nuclear, Environment

1. Introduction

Collapse of the Twin-tower, 110-storey World Trade Center (WTC) in New York, USA on September 11, 2001 due to terrorist attack by crashing two Boeing 767 aircrafts into the building and triggering explosions with fire ushered a new vista for research on fire hazards. The flame temperature of 1727 °C of avionic fuel melted and buckled the steel columns. This incident has renewed interest in fire resistant design of structures [1].

The approach of passive fire protection includes structural fire protection, the layout of escape routes, the fire brigade access routes and the control of combustible materials for construction [2], [3]. In a fully developed fire, the passive measures will provide sufficient fire resistance to prevent both the spread of fire and the structural collapse.

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In Indian standards, only BIS-3614 (Part-2) [4] deals with the standard fire temperature-time curve, ISO 834 specifying the fire resistance of check doors. No other Indian standard specifically talks of the fire barrier rating based on the standard fire temperature-time curve. In view of the mandatory FHA for nuclear facilities and power plants it is now pertinent to specify the fire temperature-time curve based on hydrocarbon fires and other non-hydrocarbon fires. This proposed amendment will solve the problem of standardization of indigenous Indian fire barriers of suitable fire ratings arrived on the basis of FHA using software / tool e.g. Fire Dynamics Simulator (FDS) [5] or alternative such as the zone models Ozone, MAGIC [6], CFAST [7], FIVE [8].

Fire protection provision especially the passive ones can be optimized to a great extent if we adapt the methodology [9], [10], [11] wherein the credit is taken for the inherent strength of structural members by virtue of their dimensions and weights. This way we can reduce the material requirement, construction time and cost as well to a great extent. So far most of the fire protection measures in the Indian standards are specific towards the safe escape of the personnel and not in the interest of protecting the structure against the collapse. Till date, the Indian standards including nuclear ones do not specify the specific fire modeling codes to carry out FHA nor do they specify requirements on any fire simulation to be carried out, without which the FHA is mostly prescriptive in nature.

2. Role of FHA

FHA is a comprehensive assessment approach of potential fires to ensure that preventive as well as mitigative measures are in place so as to limit the damages from fires and their damaging effects to an acceptable level. IAEA Safety Requirement # 74 out of 82 for FHA [12] states that fire protection systems, including fire detection systems and fire extinguishing systems, fire barriers (for fire containment) and smoke control systems shall be provided throughout the nuclear power plant, with due account taken of the results of the FHA.

Role of FHA is to pre-empt and protect the facility under consideration from the damaging effects of fire to an acceptable level. FHA is a proactive approach based on the principle of "*predict and correct*" rather than "*find and fix.*

The goal of FHA is to determine the expected outcome of a specific set of conditions called a fire scenario. The scenario includes details of the fire sources and combustibles present in the area of concern, area/room dimensions, contents and materials of construction, arrangement of rooms in the building, sources of combustion air, position of doors/windows/dampers: numbers, locations, ventilation flows and opening areas with height of location, characteristics of occupants, and any other details that have an effect on the outcome of interest. As fire is often simulated and analyzed for the possible scenarios and consequences in FHA, it gives more realistic picture of fire and its effects and thus can be termed as an enabler for prudent use of resources towards fire protection measures.

FHA can assess the fire in a more realistic fashion sometimes with even worst-case scenarios resulting in securing safety of plant, person and environment in a better way with better resource utilization in terms of material, cost, time, effort(man-hours) etc. FHA can also determine the adequacy of fire barrier ratings provided for various structural and non-structural members/components of a plant/facility. FHA is carried out in various stages of a project life-cycle of a plant or building - design, construction, pre-commissioning, commissioning, operation etc. So far, FHA (e.g. in India) is mandatory only for Nuclear Plants and Facilities but not for non-nuclear industries/facilities. In developed nations, the FHA is mandatory for all types of establishments, buildings - even residential ones and all types of plants and industries as required by regulatory authorities for fire safety and insurance as well. Safety and genuine claim of loss due to fire in terms of insured value can be assured and evaluated/assessed to a great extent by carrying out FHA. Bogus or False Fire Loss Claims are not uncommon in the world, which can be checked by FHA.

3. Fire Simulation

Fire modeling and simulation can be carried out in various ways. There are different fire models adopted to postulated fire scenarios based on the fire load of combustibles and inflammables, their quantity, type of combustibles, ventilation parameters such air (oxygen) flow, ventilation openings, ventilation opening height, obstructions etc. in the area under consideration.

Some of the widely used fire models are listed below which are typically applied for fire simulation in nuclear installations:

- Zone Models: CFAST, FIREWIND, BRANZFIRE, MAGIC;
- Field Models or Computational Fluid Dynamics (CFD)-based models: FDS, FLUENT, JASMINE, PHOENICS, SMARTFIRE, SOFIE, STAR-CD etc.

Among these models, CFAST [6] [2] as well as MAGIC [3] [8] as zone models and FDS [5] [6] and JASMINE [10] as field models are commonly used for fire simulation and modeling for nuclear installations and other industries/buildings as well.

Fire Dynamics Simulator (FDS) is chosen as fire model and simulation tool in this paper due to its global recognition.

FDS, being CFD model, has three basic parts:

1. An Interface to allow the user to input parameters
2. The Flow solver which models the fire using the input : Need of a Fast Solver
3. A Graphical Program to display results of the fire modeled.

FDS can also define the geometry of cable trays and cabinets with temporal and spatial variations of temperature, heat flux and smoke density etc.

The author with his colleagues have carried out FHA using FDS and Smokeview for about 2400 fire areas and rooms in Fast Reactor Fuel Cycle Facility for Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam and for Balance of Turbine Island Packages (BoTIP) of 2X700 MW_e units of Nuclear Power Plant Projects in Gujarat and Rajasthan for Nuclear Power Corporation of India Limited (NPCIL). Fire protection provision in terms of passive fire protection of structures and structural members like columns, beams, ceilings, floors, walls, truss etc. were assessed for adequacy of necessary fire protection conforming to the regulatory requirements of Atomic Energy Regulatory Board (AERB) of India.

3a. Justification of Passive Fire Protection

Justification of passive fire protection in terms of fire barrier rating can be adequately addressed by considering the following:

- Severity and thermal effects of fire are judged by the fire simulation results and fire barrier ratings are accordingly derived based on Equal Area Criterion of Actual Fire curve vs. Standard Fire Curve (e.g. ISO 834 Curve). For Oil & Gas fires, Hydrocarbon curve UL-1709 / ASTM -1529 for rapid rise in temperature needs to be adopted.

- Every structural component or structure used for passive fire protection measure has an inherent fire barrier rating which must be given credit while calculating the fire barrier rating of such passive fire protection structure. It is observed that in many cases the fire ratings based on the inherent ratings of structural members due to their thickness, width and length have fire ratings varying between 10 to 30 minutes or even more without any additional fire protective coating or passive protection. These inherent fire ratings are given credit in USNRC NUREG -1805 [10] and also in SFPE & NFPA Handbook [11] which are logically correct. Such inherent fire rating has been leveraged for many structural members in some of the nuclear projects resulting in saving of costly project resources (material, cost, effort, construction time, environment etc.).

- Fire ratings are correlated with the geometric dimensions and weights of the structural members [10], [11] which is called the Credit to Inherent Fire Ratings of Structural Members.

- European norms have also given credit to fire protection provisions (sprinkler, detection, automatic alarm transmission, firemen …) while arriving at fire ratings of passive fire protection [15].

3b. Fire Simulation Result

Using FDS fire modeling and simulation for some plant areas sample input and outputs are provided in Fig. 1, 2, 3 at the end under Appendix. Sample Input is an FDS file written in .text format using the FDS Commands and syntax considering the properties of the materials, geometries (dimensions), Ventilation flows, opening, elevation along with arrangement of materials and obstructions present in the fire area/compartment. Fire simulation (based on FDS modeling and simulation) sample results for Temperature vs. Time Curves for Control Room Cabinet Fire, Heat Flux for a plant area under fire, Temperature-Time Curves for structural members and Cable tray in a plant area under fire are as given in Fig. 1, Fig. 2 and Fig. 3 respectively.

4. Fire Protection Provision of Structures

Fire protection provision of structures, mainly in terms of passive fire protection of structural components, are discussed in this paper. Applying Fire Protective Paints, Fire Boards, Intumescent, Cement / RCC / brick-wall encasing the members etc. are the few possible treatments that are provided with the structural members or structures. The fire barrier ratings of these are evaluated based on fire simulation outputs and comparing the temperatures with reference to the Standard Fire Curve of ISO 834 which is recognized by the Indian Standards and Regulatory bodies. ISO-834 Standard Fire Curve is also internationally recommended and globally accepted one which shows variation of temperature with time as per the standard fire test as mentioned in [11]. As the cost of additional fire protection materials needed to be provided for the structures, say, structural steel structures for TG Building of Nuclear Power Plant (NPP) in Gujarat (KAPP-3 & 4) is often higher than even 40 % of the finished steel cost, the fire simulation based outcomes are used to reduce the cost without neglecting the safety aspects.

It is observed that appreciable cost saving (besides environmental concern) results by realistic but worst-case fire simulation-based fire ratings rather than going for prescribed values e.g. 3- hour for safety related and 1-hour for non-safety related structures everywhere in a 100 m X80 m X45 m Turbo-Generator Building made of structural steel. A rough estimate shows that cost-saving in terms of additional fire protection paint coating is observed to be 1 Million USD for a steel structure turbine building of a single 700 MWe NPP unit in Kakrapar, Gujarat, India.

This is based on the fact that a very simple calculation of Total Fire-Protective Paint Applicable Surface Area of Structural Steel (beams, columns and truss) for the aforesaid NPP of twin unit would be around 45000 m^2 and the differential cost of Indian Rs. (INR) 1000 for a 3-hour Fire Paint vs. 1-hour Fire Paint would result in around 0.75 Million USD which is close to 1 Million USD in terms of saving in Fire-Paint cost alone. Besides this there would be labour cost and differential cost of applying varying fire-rated fire barriers (doors, walls, cable wraps, fire-protected cable penetration seals.. etc.) for 3-hour, 1-hour and ½ hour would result in appreciable savings. Differential treatment of fire protection in terms of fire rating (whether 3-hour or 1 hour or ½ hour) is based on the fire hazard analysis using fire modeling & simulation techniques along with due credit given to Inherent Fire Ratings as explained in next section of this paper which is a huge cost saving factor.

5. Regulatory Support & Discussion

Lots of Safety Regulatory Support is needed in view of safety and environment from resource utilization point of view. Unless the regulatory amendments are implemented, industries are not going to follow the fire safety measures based on FHA.

Present-day regulatory fire safety measures followed by most of the non-nuclear industries/sectors use Tariff Advisory Committee (TAC) guidelines which are age-old and on the verge of being obsolete. Indian Standards on Fire safety needs to be changed along with fire safety rules. Some fire safety rules/codes have changed but the changes are not adequately up-to-date. For example: BIS-3034 on Fire Protection of Electric Power Generating & Distribution Stations has been updated since 2003. Many national codes allow a 50 % reduction in the fire resistance of structural members, if the building under consideration is provided with sprinklers. However, in India no such codal provision exists till now. Even Eurocodes [9] [15] suggest that for calculating the fire resistance rating, the full fire load in a building provided with sprinklers to be taken as 60 % of the design full load.

It makes sense to make regulatory statement such as: “Where fire barriers are used for separation, a 3-hour fire resistance rating should be provided unless the FHA can demonstrate something less is adequate” rather than stating “Unless otherwise specified ‘adequate’ barrier rating means, rating as calculated as per fire hazard analysis (FHA), or a minimum of 1-hour rating, whichever is more” as per [14]. Hence, suitable amendment in regulation/code is needed. Unless FHA can demonstrate that something less is adequate in fire rating value, prescribed territorial regulatory requirement is to be followed because FHA derived result justifies the basis of fire protection adequacy [13].

Many regulatory bodies impose the compulsory application of stipulated fire resistance ratings even after it is proven that FHA using fire dynamics simulation shows lower fire resistance ratings which are already catered by the inherent fire resistance ratings of the structural members because every structural member has its own inherent fire resistance rating derivable on the basis of its parameters like weight-to-heated perimeter (W/D) ratio, where W is the weight [lbs./ft. of length] and D is the heated perimeter [inches] of the structural member with W/D ratio is the factor that allows the interpolation of fire protective coating thicknesses. This is as per Society of Fire Protection Engineers (SFPE) Handbook on Fire Protection Engineering [11] and also NUREG-1805 [10] by U.S. NRC. Based on theoretical and experimental studies, the following formulae have been developed for calculating the fire resistance rating of unprotected steel columns [10], [11]:

$$R = 10.3\left(\frac{W}{D}\right)^{0.7} \; for \; \frac{W}{D} < 10 \quad \text{and} \quad R = 8.3\left(\frac{W}{D}\right)^{0.8} \; for \; \frac{W}{D} \geq 10$$

Where, R = Fire Resistance Rating in minutes,
W = Weight of steel column per linear foot in lb/ft. and D = Heated Perimeter in inches.

6. Conclusion

This paper finally concludes the following:

6.1 Need of FHA for assessing and justifying the fire protection measures applied to structure and its member based on fire dynamics simulation outcomes and analyses.

6.2 Credit should be given to Inherent Fire Rating of a structural member or structure along with FHA / fire simulation derived parameters and fire ratings so as to optimize between cost and safety but without curtailing the safety aspect. Huge Saving in Project Resources in terms of Cost, Material, Manhour, Construction Time etc. do result if Fire Protection Measures (active and passive) are implemented based on FHA using Fire Modeling & Simulation coupled with due Credit to Inherent Fire Rating of Structural Members and Structures. Cost reduction based on differential fire ratings justified by FHA using fire modeling & simulation and inherent fire ratings is the focal point of this paper.

7. Acknowledgement

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9. Appendix

9.1 Sample Fire Modeling & Simulation (FDS) Input:

```
&HEAD CHID='XYZ_AREA', TITLE='fire in XYZ area' /

&MESH IJK=96, 56, 24, XB=0.0, 24.0, 0.0, 14.0, 0.0, 5.7 /

&TIME T_END=10000. /

&DUMP DT_HRR=10., DT_DEVC=10./

&MISC SURF_DEFAULT='WALL', TMPA=38, /

&RADI RADIATIVE_FRACTION=0.35 /

&MATL ID = 'CONCRETE'

    DENSITY = 2400.

    CONDUCTIVITY = 1.6

    SPECIFIC_HEAT = 0.75 /

&MATL ID = 'STEEL'

    SPECIFIC_HEAT = 0.465

    CONDUCTIVITY = 54.
```

```
    DENSITY = 7850. /
&MATL ID          = 'COPPER'
    SPECIFIC_HEAT = 0.38
    CONDUCTIVITY  = 387.
    DENSITY       = 8940. /
&MATL ID                 = 'PVC'
    CONDUCTIVITY         = 0.19
    SPECIFIC_HEAT        = 0.9
    DENSITY              = 1400.
    N_REACTIONS          = 1.
    HEAT_OF_REACTION     = 17950.
    HEAT_OF_COMBUSTION   = 25000.
    REFERENCE_TEMPERATURE = 150.
    NU_FUEL       = 1.0/
&SURF ID = 'CEILING'
    COLOR = 'SILVER'
    MATL_ID   = 'CONCRETE'
    THICKNESS = 0.2 /
&SURF ID = 'BEAM'
    COLOR = 'TOMATO'
    MATL_ID = 'STEEL'
    BACKING = 'EXPOSED'
    THICKNESS = 0.05 /
&SURF ID       = 'SHEET METAL'
    MATL_ID   = 'STEEL'
      COLOR     = 'SILVER'
    THICKNESS = 0.0013 /
&OBST XB=0.0, 24.0, 0.0, 14.0, 5.65, 5.7, SURF_ID= 'CEILING'/
```

Cables

```
&SURF ID                  = 'CABLE'
     COLOR                = 'BLACK'
     MATL_ID(1,1:2)       = 'PVC','COPPER'
     MATL_MASS_FRACTION(1,1:2) = 0.33,0.67
     THICKNESS            = 0.030
     BACKING              = 'EXPOSED' /
&SURF ID        = 'TRAY'
     COLOR      = 'SILVER'
     MATL_ID    = 'STEEL'
     THICKNESS  = 0.003 /
……..
```

Cable Tray

```
&OBST XB= 13.0, 13.6, 0.0, 1.01, 1.45, 1.49, SURF_ID= 'CABLE'/ CABLES 106.75
&OBST XB= 13.0, 13.0, 0.0, 1.01, 1.45, 1.55, SURF_ID= 'TRAY'/ TRAY SIDE
&OBST XB= 13.6, 13.6, 0.0, 1.01, 1.45, 1.55, SURF_ID= 'TRAY'/TRAY SIDE
&OBST XB= 13.0, 13.6, 0.0, 1.01, 1.72, 1.76, SURF_ID= 'CABLE'/ CABLES 107.02M
&OBST XB= 13.0, 13.0, 0.0, 1.01, 1.72, 1.82, SURF_ID= 'TRAY'/ TRAY SIDE
&OBST XB= 13.6, 13.6, 0.0, 1.01, 1.72, 1.82, SURF_ID= 'TRAY'/TRAY SIDE
……
```

Fire

```
&SURF ID='FIRE', HRRPUA=1794, RAMP_Q='fireramp', COLOR='RASPBERRY' /
&RAMP ID='fireramp', T=0.0, F=0.0 /
&RAMP ID='fireramp', T=300.0, F=1.0 /
&RAMP ID='fireramp', T=1560.0, F=1.0 /
&RAMP ID='fireramp', T=2400.0, F=0.0 /
&OBST XB=12.0, 13.0, 5.0, 6.0, 2.6, 2.9 /
&VENT XB=12.0, 13.0, 5.0, 6.0, 2.9, 2.9, SURF_ID='FIRE' /
```

Ventilation

```
&SURF ID='INFLOW',VEL=-5, /
```

```
&VENT MB= 'YMIN', SURF_ID='INFLOW' / inflow through y=0 plane
&VENT MB= 'YMAX', SURF_ID='OPEN' / outlet
&VENT MB= 'XMIN', SURF_ID='OPEN' / left side
&VENT MB= 'ZMIN', SURF_ID='OPEN' / bottom
&SLCF PBX= 12.0, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
 &SLCF PBX= 12.0, QUANTITY='OPTICAL DENSITY', VECTOR=.TRUE. /
&SLCF PBX=12.0, QUANTITY='soot density' /
&BNDF QUANTITY='BURNING_RATE' /
&BNDF QUANTITY='NET HEAT FLUX' /
&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /
&BNDF QUANTITY='WALL TEMPERATURE'/
&DEVC XYZ =12.5, 5.5, 3.0, QUANTITY='TEMPERATURE',ID='FLAME TEMP' /
&DEVC XYZ =0.1, 2.4, 4.0, QUANTITY = 'TEMPERATURE', ID='TRAY NO 21 TO CB' /
&DEVC XYZ =0.1, 4.3, 4.0, QUANTITY = 'TEMPERATURE', ID='TRAY NO 22 TO CB' /
&DEVC XYZ =0.1, 5.0, 4.0, QUANTITY = 'TEMPERATURE', ID='TRAY NO 23 TO CB' /
&DEVC XYZ =0.1, 6.3, 4.0, QUANTITY = 'TEMPERATURE', ID='TRAY NO 24 TO CB' /
………..
&TAIL /   End of file
```

9.2 Sample Fire Modeling & Simulation (FDS) Results / Outputs are depicted under Fig.1, Fig.2 and Fig.3:

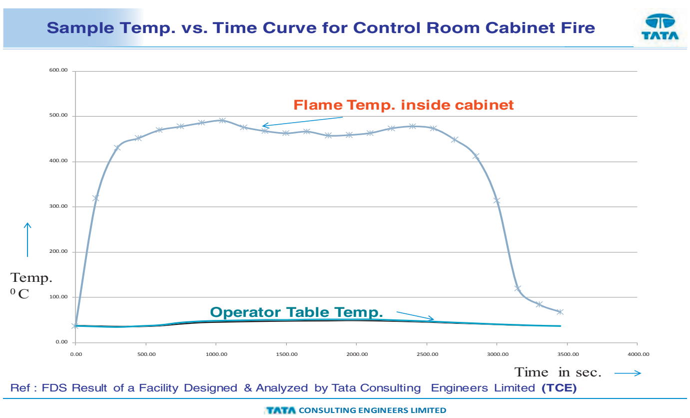

Fig. 1

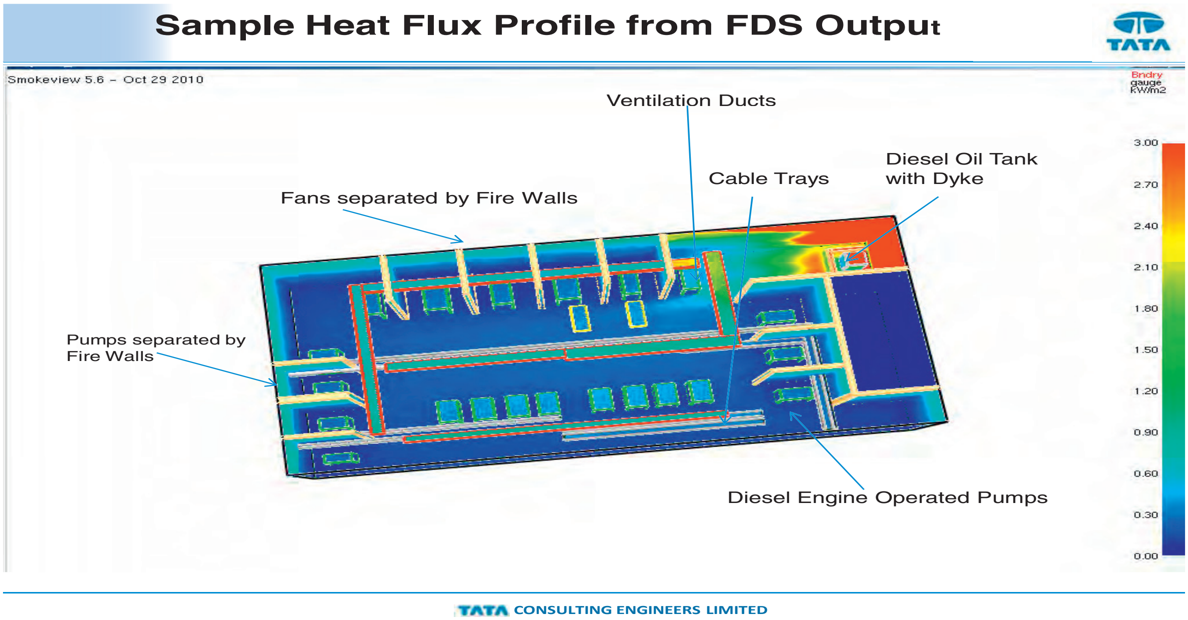
Sample Heat Flux Profile from FDS Output
TATA
Smokeview 5.6 – Oct 29 2010
Bndry gauge kW/m2
3.00
2.70
2.40
2.10
1.80
1.50
1.20
0.90
0.60
0.30
0.00
Ventilation Ducts
Cable Trays
Diesel Oil Tank with Dyke
Fans separated by Fire Walls
Pumps separated by Fire Walls
Diesel Engine Operated Pumps
TATA CONSULTING ENGINEERS LIMITED

Fig. 2

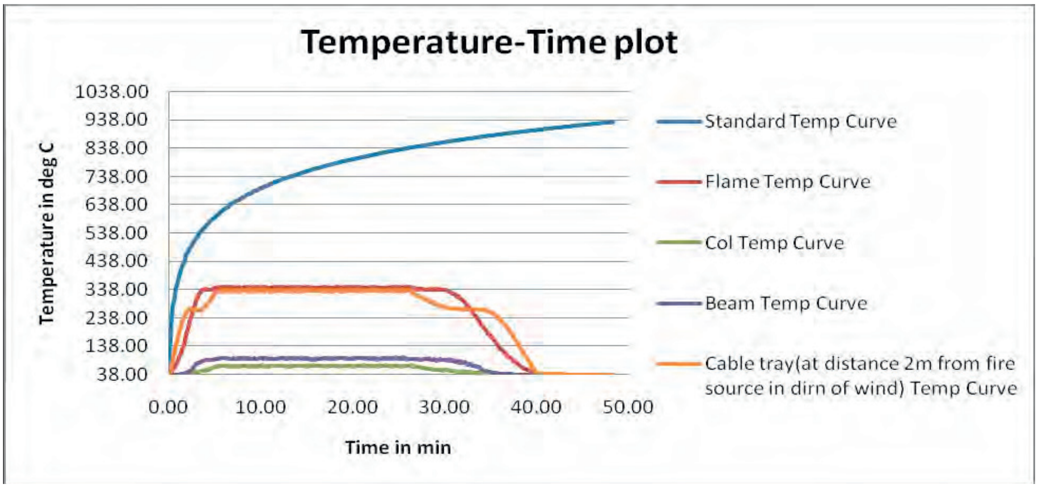
Temperature-Time plot
1038.00
938.00
838.00
738.00
638.00
538.00
438.00
338.00
238.00
138.00
38.00
Temperature in deg C
0.00
10.00
20.00
30.00
40.00
50.00
Time in min
Standard Temp Curve
Flame Temp Curve
Col Temp Curve
Beam Temp Curve
Cable tray(at distance 2m from fire source in dirn of wind) Temp Curve

Fig. 3